

## METHOD FOR FABRICATING A MOLD FOR A MICROLENS

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5

## BACKGROUND OF THE INVENTION

## Field of the Invention

The present invention relates to a fabrication method of a  
10 microstructure, a fabrication method of a mold or a master of a mold  
(in the specification the term "mold" is chiefly used in a broad sense  
including both a mold and a master of a mold) for forming a  
microstructure, a fabrication method of a microstructure using the  
mold, and so forth. This invention particularly relates to a mold for a  
15 microlens or a microlens array, a fabrication method of the mold, and  
a fabrication method of the microlens or the microlens array using the  
mold.

## Description of the Related Background Art

20 A microlens array typically has a structure of arrayed minute  
lenses each having a diameter from about 2 to 3 microns to about 200  
or 300 microns and an approximately semispherical profile. The  
microlens array is usable in a variety of applications, such as  
liquid-crystal display devices, light receivers and inter-fiber  
25 connections in optical communication systems.

Meanwhile, earnest developments have been made with  
respect to a surface emitting laser and the like which

1 can be readily arranged in an array form at narrow  
pitches between the devices. Accordingly, there exists  
a significant need for a microlens array with narrow  
lens intervals and a large numerical aperture (NA).

5 Likewise, a light receiving device, such as a charge  
coupled device (CCD), has been more and more downsized  
as semiconductor processing techniques develop and  
advance. Therefore, also in this field, the need for  
a microlens array with narrow lens intervals and a  
10 large NA is increasing.

In the field of such a microlens, a desirable structure  
is a microlens with a large light-condensing efficiency  
which can highly efficiently utilize light incident on  
its lens surface.

15 Further, similar desires exist in prospective fields  
of optical information processing, such as optical  
parallel processing-operations and optical interconnections.  
Furthermore, display devices of active or self-radiating  
types, such as electroluminescent (EL) panels, have  
20 been enthusiastically studied and developed, and a  
highly-defined and highly-luminous display has been  
thus proposed. In such a display, there is a heightened  
desire for a microlens array which can be produced at  
a relatively low cost and with a large area as well  
25 as with a small lens size and a large NA.

There are presently a number of prior art methods  
for fabricating microlenses.

1        In a prior art microlens-array fabrication method  
using an ion exchange method (see M. Oikawa, et al.,  
Jpn. J. Appl. Phys. 20(1) L51-54, 1981), a refractive  
index is raised at plural places in a substrate of  
5 multi-component glass by using an ion exchange method.  
A plurality of lenses are thus formed at high-refractive  
index places. In this method, however, the lens diameter  
cannot be large, compared with intervals between lenses.  
Hence, it is difficult to design a lens with a large NA.  
10 Further, the fabrication of a large-area microlens array  
is not easy since a large scale manufacturing apparatus,  
such as an ion diffusion apparatus, is required to  
produce such a microlens array. Moreover, an ion exchange  
process is needed for each glass, in contrast with a  
15 molding method using a mold. Therefore, variations of  
lens quality, such as a focal length, are likely to  
increase between lots unless the management of  
fabrication conditions in the manufacturing apparatus is  
carefully conducted. In addition to the above, the cost  
20 of this method is relatively high, as compared with the  
method using a mold.

Further, in the ion exchange method, alkaline  
ions for ion-exchange are indispensable in a glass  
substrate, and therefore, the material of the substrate is  
25 limited to alkaline glass. The alkaline glass is,  
however, unfit for a semiconductor-based device which  
needs to be free of alkaline ions. Furthermore, since

1 a thermal expansion coefficient of the glass substrate  
greatly differs from that of a substrate of a light  
radiating or receiving device, misalignment between the  
microlens array and the devices is likely to occur due  
5 to a misfit between their thermal expansion coefficients  
as an integration density of the devices increases.

Moreover, a compressive strain inherently remains  
on the glass surface which is processed by the ion  
exchange method. Accordingly, the glass tends to warp,  
10 and hence, a difficulty in joining or bonding between  
the glass and the light radiating or receiving device  
increases as the size of the microlens array increases.

In another prior art microlens-array fabrication  
method using a resist reflow (or melting) method (see  
15 D. Daly, et al., Proc. Microlens Arrays Teddington.,  
p23-34, 1991), resin formed on a substrate is  
cylindrically patterned using a photolithography  
process and a microlens array is fabricated by heating  
and reflowing the resin. Lenses having various  
20 shapes can be fabricated at a low cost by this resist  
reflow method. Further, this method has no problems  
of thermal expansion coefficient, warp and so forth, in  
contrast with the ion exchange method.

In the resist reflow method, however, the profile  
25 of the microlens is strongly dependent on the thickness  
of resin, wetting condition between the substrate and  
resin, and heating temperature. Therefore, variations

1 between lots are likely to occur while a fabrication  
reproducibility per a single substrate surface is high.

Further, when adjacent lenses are brought into  
contact with each other due to the reflow, a desired  
5 lens profile cannot be secured due to the surface tension.  
Accordingly, it is difficult to achieve a high light-  
condensing efficiency by bringing the adjacent lenses  
into contact and decreasing an unused area between the  
lenses. Furthermore, when a lens diameter from about  
10 20 or 30 microns to about 200 or 300 microns is  
desired, the thickness of deposited resin must be large  
enough to obtain a spherical surface by the reflow. It  
is, however, difficult to uniformly and thickly deposit  
the resin material having desired optical characteristics  
15 (such as refractive index and optical transmissivity).  
Thus, it is difficult to produce a microlens with a  
large curvature and a relatively large diameter.

In another prior art method, an original plate of a  
microlens is fabricated, lens material is deposited on  
20 the original plate and the deposited lens material is  
then separated. The original plate or mold is fabricated  
by an electron-beam lithography method (see Japanese  
Patent Application Laid-Open No. 1 (1989)-261601), or a  
wet etching method (see Japanese Patent Application  
25 Laid-Open No. 5 (1993)-303009). In these methods, the  
microlens can be reproduced by molding, variations between  
lots are unlikely to occur, and the microlens can be

1 fabricated at a low cost. Further, the problems of  
alignment error and warp due to the difference in the  
thermal expansion coefficient can be solved, in contrast  
with the ion exchange method.

5 In the electron-beam lithography method, however, an  
electron-beam lithographic apparatus is expensive and a  
large investment in equipment is needed. Further, it is  
difficult to fabricate a mold having a large area more  
than 100 cm<sup>2</sup> (10 cm-square) because the electron beam  
10 impact area is limited.

Further, in the wet etching method, since an  
isotropic etching using a chemical action is principally  
employed, an etching of the metal plate into a desired  
profile cannot be achieved if composition and crystalline  
15 structure of the metal plate vary even slightly. In  
addition, etching will continue unless the plate is  
washed immediately after a desired shape is obtained.  
When a minute microlens is to be formed, a deviation of the  
shape from a desired one is possible due to an etching  
20 lasting during a period from the time a desired profile  
is reached to time the microlens is reached.

Further, there also exists a mold fabrication method  
using an electroplating technique (see Japanese Patent  
Application Laid-Open No. 6 (1994)-27302). In this method,  
25 an insulating film having a conductive layer formed on one  
surface thereof and an opening is used, the electroplating  
is performed with the conductive layer acting as a

1 cathode, and a protruding portion acting as a mother mold  
for a lens is formed on a surface of the insulating  
film. The process of fabricating the mold by this method  
is simple, and cost is reduced. Similar such methods  
5 are also disclosed in Japanese Patent Application  
Laid-Open No. 8 (1996)-258051 and Japanese Patent  
Publication No. 64 (1989)-10169.

The problem occurring when a plated layer is formed  
in an opening by the electroplating technique will  
10 be described by reference to Figs. 1A-1D and 2.  
Figs. 1A-1D illustrate electroplating growth steps at  
the time when the electroplating is performed on  
an insulating body 202 with an opening 203 having  
a diameter  $\phi$  and a cathode of an electrically-conductive  
15 body 201. Fig. 2 illustrates a cross-section of a  
mold shown in Fig. 1D.

During the electroplating growth process, a flat  
portion 210 of a plated layer 204 in the opening 203  
gradually decreases as the plated layer 204 grows  
20 (Figs. 1B and 1C), and a surface of the plated layer 204  
comes to have a maximum curvature (Fig. 1D). After  
that, a bottom diameter  $\Psi$  of the plated layer 204  
increases as the plated layer 204 grows. A radius of  
curvature thus increases accordingly.

25 Where the plated layer 204 has the flat portion as  
illustrated in Figs. 1B and 1C, the illustrated structure  
cannot be used as a mold for a lens since image-forming

1 cannot be achieved at a lens portion corresponding to the  
flat portion. According to this method, a radius of  
curvature near an optical axis of the lens mold  
increases as the diameter  $\phi$  of the opening 203  
5 increases. Where the lens mold is to be fabricated, the  
radius of curvature of the plated layer 204 cannot be  
decreased when the diameter  $\phi$  of the opening is large.  
Thus, it is often difficult to fabricate a lens mold  
having a desired radius  $R$  of curvature.

10 Further, where a profile of the plated layer  
deviates from a semispherical shape as illustrated in  
Fig. 2, a radius  $S$  of curvature of a side surface of  
the plated layer differs from that  $R$  of a portion of the  
lens near its optical axis and positions of their  
15 curvature centers  $C$  and  $C'$  differ from each other. Thus,  
the curvature center  $C'$  of the side surface does not  
lie on the optical axis. As a result, a side surface of  
a microlens fabricated using such a mold cannot be  
used, and hence, the lens will inevitably have a small NA.

20 Furthermore, it is apparently difficult to precisely  
form a microlens with a diameter less than several  
hundreds of microns (particularly, less than about three  
hundred microns) and a radius of curvature less  
than  $200\ \mu\text{m}$  at an uppermost spherical portion, by the prior  
25 art lens fabrication techniques.



## 1 SUMMARY OF THE INVENTION

An object of the present invention is to provide a fabrication method of fabricating a microstructure (typically a microlens such as a semispherical microlens, a flyeye lens and a lenticular lens) flexibly, readily and stably, a fabrication method of a mold for forming a microstructure, a fabrication method of a microstructure using the mold, and so forth. More particularly, it is an object to provide a mold for a microlens or a microlens array which can be readily increased in size, readily fabricated with good controllability and at a relatively low cost and have a desired radius of curvature, or which has a large NA. It is an additional object to provide a fabrication method of such a mold, and a fabrication method of the microlens or the microlens array using the mold.

The present invention is generally directed to a mold for a microlens which includes a substrate at least a portion of which is conductive, such as an electrically-conductive substrate or a substrate with an electrode layer or an insulating or conductive substrate at least a portion of which is electrically conductive or insulating, respectively, an insulating mask layer formed on the substrate and including an opening or plural openings (the opening typically has a circular or slit-like shape), and a plated layer electroplated in the opening and on the mask layer. Herein, (R) is a

1 radius of curvature of the plated layer right above  
the opening and at least one of (a) and (b) is met,  
wherein in (a) a diameter or width ( $\phi$ ) of the opening  
has a relation of  $\phi \leq 0.35R$  and in (b) the diameter  
5 or width ( $\phi$ ) of the opening is  $\phi \leq 10 \mu m$ .

The relation of  $\phi \leq 0.35R$  is especially significant  
when the diameter or width ( $\phi$ ) of the opening is  
above  $10 \mu m$ .

Specifically, the following structures can be  
10 adopted based on the above fundamental structure.

A plurality of the plated layers are formed in  
and around the openings, respectively, and adjacent  
plated layers of the plated layers are continuously  
formed. The substrate can be composed of silicon,  
15 glass, quartz or a polymeric substance. Further,  
the mask layer may be formed of a photoresist layer.

The present invention is also generally directed to  
a fabrication method of a mold for a microlens  
including the following steps:

- 20 preparing the above substrate;
- forming an insulating mask layer on the conductive  
portion of the substrate;
- forming an opening in the mask layer to expose the  
conductive portion of the substrate at the opening; and
- 25 performing electroplating using the conductive  
portion of the substrate as a cathode to deposit a plated  
layer in the opening and on the mask layer. When the

1 substrate has an electrode layer, it is employed  
during electroplating; otherwise the conductive substrate  
or conductive surface of an insulating substrate is so  
employed.

5 The electroplating is performed satisfying at least  
one of a first condition or second condition. The first  
condition is that the plated layer has a flat portion  
formed at the beginning of the electroplating, during  
which a bottom diameter or width ( $\Psi$ ) of the plated layer  
10 coincides with a diameter or width ( $\phi$ ) of the opening,  
and a radius ( $R$ ) of curvature of the plated layer right  
above the opening and the diameter or width ( $\phi$ ) of  
the opening has a relation of  $\phi \leq 0.35R$ . The second  
condition is that a plated layer having a convex  
15 profile is formed at the beginning of the electroplating.

The relation of  $\phi \leq 0.35R$  is especially significant  
when the diameter or width ( $\phi$ ) of the opening is  
above 10  $\mu\text{m}$ .

It is especially significant that the diameter or  
20 width ( $\phi$ ) of the opening is below 10  $\mu\text{m}$  in order to  
meet the second condition.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1A-1D are cross-sectional views illustrating  
25 prior art electroplating growth steps, respectively.

Fig. 2 is a cross-sectional view illustrating a  
radius of curvature of a plated layer.

1 Figs. 3A-3E are cross-sectional views illustrating electroplating growth steps in a fabrication method of a microlens mold of a first embodiment according to the present invention, respectively.

5 Fig. 4 is a cross-sectional view illustrating an electroplating apparatus used in the present invention.

Fig. 5 is a graph illustrating a minimum radius of curvature of a plated layer.

Fig. 6 is a graph illustrating experimental results  
10 of radii of curvature near the optical axis of plated layers and bottom diameters of plated layers in the first embodiment.

Fig. 7 is a graph illustrating results of minimum radii of curvature and opening diameters  $\phi$  in the  
15 first embodiment.

Figs. 8A-8D are cross-sectional views illustrating electroplating growth steps in a fabrication method of a microlens mold of a second embodiment according to the present invention, respectively.

20 Fig. 9 is a view illustrating an estimation method of a semispherical profile in the second embodiment.

Fig. 10 is a graph illustrating results of radii  $R$  of curvature near the optical axis of plated layers right above openings and virtual radii  $r$  of curvature in  
25 the second embodiment.

Figs. 11A-11E are cross-sectional views illustrating fabrication steps in a method for electroplating a mold

1 on a mold master, respectively.

Figs. 12A-12C are cross-sectional views illustrating fabrication steps in a method for fabricating a microlens array according to the present invention, respectively.

5 Figs. 13A-13C are cross-sectional views illustrating fabrication steps in another method for fabricating a microlens array according to the present invention, respectively.

Fig. 14 is a perspective view illustrating a mold  
10 for a lenticular lens array according to the present invention.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

Various aspects of molds for forming a microlens and  
15 methods of fabricating the same of this invention will be initially described.

A plurality of the plated layers can be plated in and around the openings, respectively, and adjacent plated layers of the plated layers can be continuously  
20 formed in the electroplating step. The flyeye lens or the like can be formed using this method.

The electroplating is preferably performed while an electroplating bath is not caused to flow on the substrate in the electroplating step. A reason therefor  
25 is later described.

The electroplating can be one of nickel electroplating, copper electroplating and chrome electroplating in the

1 electroplating step.

A step of forming a mold on the substrate with the plated layer and a step of separating the mold from the substrate can be further added to fabricate a microlens mold which has an inverted profile of the above mold.

A step of forming a sacrificial layer on the substrate after the plated layer forming step can also be added.

In this case, the sacrificial layer is removed to separate the mold from the substrate in the mold separating

10 step. This process of introducing the sacrificial layer will be described with reference to Figs. 11A-11E. A sacrificial layer 37 is formed on a mold master 31-35 fabricated by the electroplating as illustrated in

Fig. 11A: A mold electrode 38 for electroplating is then formed as illustrated in Fig. 11B. The

electroplating is performed using the the mold electrode 38 as a cathode in the electroplating liquid containing metal ions to form a mold 39 as illustrated in Fig. 11C. After that, the sacrificial layer 37 is

20 etched and removed such that the mold 39 with the mold electrode 38 can be separated from the substrate 31 with the plated layer 35 as illustrated in Fig. 11D.

The mold electrode 38 is then etched and removed to form the mold 39 as illustrated in Fig. 11E.

25 In this process the mold electrode 38 is removed.

However, if it is unlikely that the lens surface will be contaminated by the mold electrode 38 or that the the mold

1 electrode 38 will be damaged due to its small yield  
stress during the process of forming a microlens by  
molding, then mold electrode 38 need not be removed.  
The electrode 32 can be used as a sacrificial layer  
5 without forming a separate sacrificial layer 37, even  
though sacrificial layer 37 is shown formed on plated  
layer 35 and mask layer 33 in the fabrication process  
of Figs. 11A-11E.

Further, between the electroplating step of Fig. 11C  
10 and the mold separating step in Fig. 11D, the electrode  
layer 32 may be etched and removed, and the plated  
layer 35 may be etched and removed. The mold 39 in  
Fig. 11E can be thus formed. According to this method,  
the fabrication time can be shortened since only the flat  
15 electrode layer 32 (not the complicated sacrificial  
layer 37) needs to be removed.

Furthermore, the substrate and the plated layer may  
be sequentially removed to separate the mold from the  
substrate in the mold separating step. The mold may also  
20 be mechanically separated from the substrate in the  
mold separating step.

In the mold forming step, the mold can be formed by  
electroplating or by coating mold material on the  
substrate with the plated layer.

25 In the electroplating step, size and profile of the  
plated layer can be controlled by controlling electroplating  
time and electroplating temperature. Here, plural

1 openings may be formed in the mask layer, and the  
electroplating time and temperature can be controlled  
such that plated layers respectively corresponding to  
the plural openings can be continuously formed. Such  
5 a mold can be used as a mold for a flyeye lens, a  
lenticular lens or the like.

As the above separating method, though the mold  
can be mechanically separated from the substrate,  
the mold is likely to be deformed when the mold is  
10 large in area. Therefore, the method of sequentially  
etching the substrate, the mask layer and the plated  
layer can be adopted as described above to solve such  
a problem. Further, where the mold is formed after the  
sacrificial layer is formed on the substrate with the  
15 plated layer, the material of the sacrificial layer should  
be selected such that the mold cannot be corroded by an  
etchant for etching the sacrificial layer. When neither  
the plated layer nor the substrate can be corroded by  
the etchant for etching the sacrificial layer, the  
20 substrate with the plated layer can be employed as a  
master for the mold many times. In this case, a second  
mold needs to be fabricated by the same method only  
when the original mold is contaminated or damaged after  
plural uses thereof.

25 Any material, such as resin, metal and insulating  
substance, can be used as the material for the microlens  
mold so long as the material can be coated on the



1 substrate with the plated layer and separated therefrom.

As a simple fabrication method of the mold, there is  
a method in which metal, fused glass or glass-dissolved  
solution is coated on the substrate with the plated  
5 layer, and the material is separated by the above  
separating method after being hardened. In this case, a  
metal material is selected, which will neither thermally  
damage nor alloy the substrate and the plated layer.

The present invention is also generally directed to  
10 a fabrication method of a microlens mold using the  
above mold, in which lens material such as resin is  
coated in the microlens mold and the microlens is  
formed by separating the lens material from the mold.

Another lens material having a different refractive  
15 index can be coated on the above separated lens material  
and hardened to form a microlens.

A microlens can be formed by using the mold  
fabricated by the above method. Thus, microlenses or  
microlens arrays having the same profile can be readily  
20 formed at a relatively low cost. As material of the  
microlens, material readily separable from the microlens  
mold can be used.

Meanwhile, any material, such as metal, semiconductor  
(a silicon wafer or the like) and insulating substance  
25 (such as glass, quartz and polymer film), can be  
used as the substrate material. When the metal material  
is used as the substrate, there is no need to form

1 the electrode layer. Further, when the semiconductor is  
used, the electrode layer is not necessarily needed  
if the semiconductor has enough conductivity to enable  
electroplating. However, where metal or semiconductor  
5 is used as the substrate, a plated layer will also  
be formed on a portion other than the microstructure  
forming portion, since the entire substrate is immersed  
in electroplating liquid. Therefore, when the plated  
layer is desired to be formed on a predetermined portion  
10 only, the insulating substance can be preferably used as  
the substrate. Alternatively, a metal or semiconductor,  
whose surface is partially insulated, may also be used.

Since the substrate is used as the mold, the  
substrate is preferably composed of a substrate with  
15 little waviness and low surface roughness. As the substrate,  
metal plate, glass substrate, silicon wafer or the like  
with an excellent flatness can be preferably used because  
the substrate has a possibility of warping due to an inner  
stress or thermal stress of the plated layer.

20 The material of the electrode layer is selected from  
materials which are not corrosive to the electroplating  
liquid used since the electrode layer is exposed to the  
electroplating liquid. The mask layer may be formed of  
any inorganic or organic insulating material that is  
25 also anticorrosive to the electroplating liquid.

When a thick electrode layer or a thick mask layer  
is formed on the substrate, its surface roughness may

1 increase depending on the particular forming method.  
Accordingly, a thin-film forming method, such as  
a vacuum-evaporation method, a spin-coat method and  
a dip method is used as a method for forming the  
5 electrode layer and the mask layer.

A process for forming the opening in the mask  
layer in this case will be described. The opening  
is formed in the mask layer by photolithography and  
etching which can provide a minute or narrow opening.  
10 After the mask layer is formed, an opening pattern of  
photoresist is formed on the mask layer by  
photolithography. An opening pattern is formed in the  
mask layer using the photoresist as a mask. The  
photoresist is then removed to form a desired opening  
15 in the mask layer. A photoresist may be used as a  
material of the mask layer. When the photoresist is  
used, the etching step of the mask layer material can  
be omitted. Therefore, a mask layer of a photoresist is  
preferable.

20 When the electroplating is conducted, there is a  
possibility that the substrate will warp due to an inner  
stress of the plated layer or a thermal stress that may be  
caused when the temperature of the electroplating bath is  
raised for the electroplating step. There is a difference  
25 over four orders of magnitude between Young's moduli or  
yield stresses of resin and metal or inorganic material.  
Accordingly, when the mask layer of resin is formed with

1 approximately the same thickness as the conductive  
layer or the plated layer, the mold is quite likely  
to warp. Further, when resin is used, there is the  
problem that the resin will swell in addition to the  
5 problem of stress. Therefore, where a mask layer of  
resin is used, it is preferable to form a thin mask  
layer, compared with the thickness of the conductive  
substrate or the substrate with the electrode layer.

The plated layer is formed by the deposition of  
10 metal ions in the electroplating bath caused by the  
electrochemical reaction. The thickness of the electroplated  
layer can be readily controlled by controlling the  
electroplating time and temperature. The following materials  
can be used as electroplating metal, for example. As  
15 a single metal, Ni, Au, Pt, Cr, Cu, Ag, Zn and the like  
can be employed. As an alloy, Cu-Zn, Sn-Co, Ni-Fe, Ni-W,  
Zn-Ni and the like can be used. Any material can  
be used so long as electroplating is possible.  
Ni, Cr and Cu are especially preferable as the  
20 electroplating material for the microlens mold because  
these metals permit a bright electroplating to be  
readily achieved.

Further, when forming the microstructure by  
electroplating, dispersion electroplating, in which  
25 dispersion particles, such as  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$  and PTFE, are  
added to the electroplating bath, can also be used.  
Mechanical strength and corrosion resistivity of the mold

1 can be improved by the dispersion particles.

These advantages and others will be more readily understood from the following detailed description of certain preferred embodiments in conjunction with the  
5 drawings.

A first embodiment of a fabrication method of a mold for a microlens will be described with reference to Figs. 3A-3E and 4-7. In the method of the first embodiment, a plated layer has a flat portion when electroplating is  
10 carried out in an opening during an initial electroplating growth step. Fig. 4 illustrates an electroplating apparatus used in the first embodiment. In Figs. 3A-3E and 4, reference numeral 1 denotes a substrate, reference numeral 2 denotes an electrode layer, reference numeral 3 denotes  
15 a mask layer, reference numeral 4 denotes an opening, reference numeral 5 denotes a plated layer, reference numeral 21 denotes a base, reference numeral 22 denotes an anode plate, reference numeral 23 denotes an electroplating bath containing metal ions, and reference  
20 numeral 24 denotes an external power source.

The structure of a substrate used in a step illustrated in Fig. 3A will be described. The electrode layer 2 is formed on the substrate 1, and the mask layer 3 is then formed thereon. Where the substrate 1 is composed  
25 of electrically-conductive substrate material, there is no need to form the electrode layer 2.

The opening 4 is then formed in the mask layer 3. Here,

1 the opening 4 has a circular shape. The substrate 1 with  
the opening 4 acting as the base 21 is immersed in the  
electroplating bath 23 containing metal ions of the electroplating  
apparatus illustrated in Fig. 4. The base 21 and  
5 the anode plate 22 are connected to the power source 24  
to cause a current flow through the bath 23 and form the  
plated layer 5 in the opening 4. Thus, the plated layer 5  
is initially formed in the opening 4 as illustrated in  
Fig. 3B. Herein, no flow of the electroplating liquid 23  
10 is caused to occur near the opening 4 during the  
electroplating process. If the electroplating liquid  
flows near the opening 4 when the plated layer 5 is  
grown in the minute opening 4, an electroplating growth  
rate on a downstream side of the flow will be larger  
15 than that on an upstream side of the flow, and hence,  
the plated layer 5 will grow asymmetrically with  
respect to a center of the opening 4. The structure  
including such an asymmetrical plated layer cannot be  
used as a microlens mold.

20 As a method of preventing flow in the electroplating  
liquid 23, there is a method of performing no stirring  
of the electroplating liquid during the electroplating.  
In another method a mesh is provided near the substrate  
to allow diffusion of the electroplating liquid, but  
25 prevents the flow thereof. In particular, the  
non-stirring method is simple and convenient. This  
non-stirring method is used in the first embodiment.

1        At the beginning of the electroplating growth, i.e., while  
a bottom diameter  $\Psi$  of the plated layer 5 is equal to  
the opening diameter  $\phi$  and no plated layer grows on the  
mask layer 3, the plated layer 5 is deposited in the  
5 opening 4 only. At this time, the plated layer 5 is  
caused to deposit in such a way that the plated layer 5  
has a flat portion which is not a concave surface. That  
is, conditions such as an applied voltage are regulated  
to achieve the above situation.

10       Ordinarily, since a current density is relatively  
large at a side portion of the electrode during the  
electroplating, the electroplating tends to occur strongly  
at an edge face of the opening 4 when a cathode has a form  
(an exposed portion of the conductive electrode layer 2)  
15 as illustrated in Fig. 3A. Hence, there is a possibility  
that the plated layer has a concave surface at the beginning  
of the electroplating. In the plated layer with such a concave  
surface, the concave portion remains near the optical  
axis (a portion right above the opening 4) even if the  
20 electroplating growth is continued. The electroplating growth  
needs to be continued for quite a long time until the plated  
layer with an approximately semispherical profile is  
reached. In such a case, it proves impossible to fabricate  
a microlens mold with a desired radius of curvature near  
25 its optical axis. As is evident from the above, the  
plated layer 5 formed in the opening 4 needs to have  
a convex profile including the flat portion to achieve the

1 fabrication of a preferable microlens mold by  
electroplating.

As the electroplating is continued, the plated layer 5  
extends onto the mask layer 3 as illustrated in Fig. 3C  
5 and the flat portion becomes smaller than that at the  
beginning of the electroplating. As the electroplating  
growth is further continued, the flat portion disappears.  
A curvature thus appears at a portion of the mold on the  
optical axis, i.e., a portion right above the opening 4,  
10 as illustrated in Figs. 3D and 3E. The plated layer 5 with  
an approximately semispherical profile is hence formed.  
Where the electroplating is effected at the opening 4 in  
the electroplating liquid containing metal ions, metal  
ions in the electroplating liquid 23 move toward the  
15 plated layer 5, and hence, deposition of the electroplating  
proceeds with its growth direction being isotropic.

With the mold for a microlens to be fabricated  
according to the above-discussed method, an experiment  
was carried out using parameters, such as the electroplating  
20 bath and electroplating conditions, in order to obtain a  
microlens mold having a desired radius  $R$  of curvature on  
its optical axis. It was found that the diameter  $\phi$  of  
the opening 4 should meet the following condition to obtain  
a desired  $R$  when the plated layer 5 with the flat portion  
25 was formed during the initial electroplating growth  
( $\Psi = \phi$ ) and the electroplating was continued ( $\Psi > \phi$ ),  
where  $\Psi$  is the bottom diameter of the plated layer 5



1 and  $\phi$  is the diameter of the opening 4:

$$\phi \leq 0.35R \quad \dots (1).$$

In other words, where the opening 5 has a predetermined diameter  $\phi$ , the plated layer 5 grown by the electroplating has a minimum radius  $R_{\min}$  of curvature. Accordingly, the opening 4 with a diameter meeting the relation (1) needs to be formed to obtain a microlens mold having a predetermined radius  $R$  of curvature.

Thus, the relation (1) showing a relation between a opening diameter or width and a minimum radius of curvature is found in this invention. With an opening diameter or width  $\phi$  outside the above condition, a plated layer with a desired radius of curvature cannot be readily obtained, although this also depends on the electroplating bath and electroplating conditions.

The minimum radius of curvature in the relation (1) will be described with reference to Fig. 5. The radius of curvature is determined in the following manner.

A mask layer with a plurality of openings is formed on a substrate, and electroplating is performed by using the substrate as a cathode and the electroplated apparatus as illustrated in Fig. 4. A surface profile of a portion right above the opening in a thus-formed plated layer is measured, and its result is reduced to a radius of curvature. A half of the bottom diameter  $\Psi$  of the plated layer 5 illustrated in Fig. 3E is used as a parameter for indicating the electroplating growth time

1 when the relation between the electroplating growth time  
and the radius of curvature is desired.

As illustrated in Figs. 3B and 3C, there is the flat  
portion on the portion of the plated layer 5 right above  
5 the opening 4 at these time periods of the electroplating  
growth, and therefore, no curvature exists (these time  
periods are indicated by a flat portion in Fig. 5). As  
the electroplating growth proceeds, the flat portion  
disappears and the plated layer 5 in turn develops a  
10 radius of curvature. As the electroplating is further  
continued, the radius of curvature of the plated layer 5  
decreases and takes the minimum radius  $R$  of curvature as  
illustrated in Fig. 5. Thereafter, as the electroplating  
growth proceeds still further, the plated layer 5 expands  
15 in size. Accordingly, the radius of curvature of the  
plated layer 5 gradually increases. The minimum radius  $R$   
of curvature depends on the diameter of the opening 4.  
The minimum radius  $R$  of curvature increases as the diameter  
of the opening 4 increases. Thus, at a predetermined  
20 diameter of the opening 4, the plated layer 5 has a  
minimum radius  $R$  of curvature.

Experiments for finding conditions enabling the  
establishment of the relation as illustrated in Fig. 5  
were performed using Ni electroplating and Cu electroplating.  
25 As an electroplating bath which can duly achieve a bright  
electroplating (electroplating for forming a bright  
layer), a Watts bath was used in the Ni electroplating.

1 An electroplating bath of copper sulfate electroplating  
was used in the Cu electroplating. The composition  
of the Watts bath was a water solution to which a  
brightener was added. This water solution consisted of  
5 the compounds-nickel sulfate hexahydrate, nickel chloride  
hexahydrate and boric acid-with their respective weight  
ratio per liter being 270 : 40 : 40. The temperature of  
the electroplating bath was set at 55 °C, and the Ni  
electroplating was performed under a constant voltage  
10 (an applied voltage is 1 V).

In the Cu electroplating, the composition of the  
bath was a water solution, to which hydrochloric acid  
at a concentration of 0.04 ml/l, was added. This water  
solution consisted of copper sulfate pentahydrate and  
15 sulfuric acid with their respective weight ratio  
per liter being 200 : 50. The temperature of the  
electroplating bath was set at 55 °C, and the Cu  
electroplating was performed under a constant voltage  
(an applied voltage is 0.3 V) as a bright condition  
20 (condition for forming a bright Cu layer).

As another Ni electroplating bath, a sulfamic acid  
bath was used, and the electroplating was performed  
under the same condition as that of the Watts bath. Herein,  
an electroplating bath available in a market was used  
25 (product name: Microfab Nil00 produced by Nippon  
Electroplating Engineers Com.).

Herein, the voltage satisfies the condition that the

1 plated layer 5 at the beginning of the electroplating has a  
flat portion, which is not concave, in the opening 4 and  
bright electroplating can be achieved. The surface profile  
was measured by a surface-shape measuring function

5 which is one of the functions of a confocal scanning laser  
microscope (a sample is moved to an objective lens side,  
and the maximum luminance position is measured during  
this move). A measurement range is equal to a length  
of the opening diameter.

10 The same substrate 1 was used irrespective of the  
electroplating bath. This substrate will be described  
as follows. A silicon wafer was thermally oxidized using  
an oxidizing gas, and layers of silicon dioxide with a  
thickness of 1  $\mu\text{m}$  were formed on opposite surfaces of  
15 the wafer. This wafer was used as the substrate 1 illustrated  
in Figs. 3A-3E. Cr and Au were continuously layered  
with thicknesses of 10 nm and 200 nm on the above wafer,  
respectively, using an electron beam vacuum-evaporation  
method which is one of thin-film forming methods. The  
20 electrode layer 2 was thus formed. Aromatic polyamide  
acid solution was then spin-coated and this coating  
was thermally treated to form the mask layer 3 of  
polyimide.

Further, coating, exposure and development of  
25 photoresist were conventionally performed using  
photolithography to form an opening in the resist. The  
mask layer 3 at the resist opening was etched by a

1 reactive ion etching using oxygen. Thus, the electrode  
layer 2 was exposed and the opening 4 was formed.  
The photoresist was removed thereafter.

As formed, the opening 4 has a circular shape.

5 Measurements were carried out with opening diameters  
of 20  $\mu\text{m}$ , 40  $\mu\text{m}$  and 80  $\mu\text{m}$  since the plated layer  
formed at the beginning of the electroplating in an  
opening with a diameter less than 10  $\mu\text{m}$  could not have a  
flat portion. The opening diameter  $\phi$  had to be  
10 above 10  $\mu\text{m}$  to form the flat portion in the plated  
layer 5 formed at the beginning of the electroplating.

Fig. 6 shows results with respect to the opening  
diameters 20  $\mu\text{m}$  and 80  $\mu\text{m}$  obtained in the Ni electroplating  
using the Watts bath. Plated layers 5 having different  
15 bottom diameters  $\Psi$  were formed on mask layers 3 with  
openings having the same diameter by varying electroplating  
time, respectively. Radii of curvature of the plated  
layers 5 right above the openings 4 on the optical  
axis were measured, and the minimum radius  $R_{\text{min}}$  of curvature  
20 was thus obtained. The minimum radius  $R_{\text{min}}$  of curvature  
was about 190  $\mu\text{m}$  when the opening diameter was 80  $\mu\text{m}$ ,  
and the minimum radius  $R_{\text{min}}$  of curvature was about 50  $\mu\text{m}$   
when 20  $\mu\text{m}$ .

Fig. 7 shows the relationship between the minimum  
25 radius  $R_{\text{min}}$  of curvature and the opening diameter  $\phi$  obtained  
by the Ni electroplating and the Cu electroplating according  
to the above method. Results obtained using the opening

1 diameters of 20  $\mu\text{m}$ , 40  $\mu\text{m}$  and 80  $\mu\text{m}$  are shown in  
the Ni electroplating (indicated by a circle in Fig 7) and  
the Cu electroplating (indicated by a triangle in Fig 7), while  
the result obtained using the opening diameter of 20  $\mu\text{m}$   
5 is shown in the sulfamic acid bath (indicated by a  
crisscross in Fig 7). No great difference could be seen  
in the minimum radius  $R_{\text{min}}$  of curvature even when the  
electroplating bath differed. From the results it  
is possible to obtain radii of curvature lying in a region  
10 above a dotted line in Fig. 7 (which represents the relation  
of  $\phi = 0.35R$ ) when the opening diameter  $\phi$  is set to a  
given value, independently of the kind of the electroplating  
bath. This means that the opening diameter  $\phi$  should  
satisfy the relation (1) to obtain a desired radius  $R$  of  
15 curvature.

In comparison with the above, with the opening  
diameter  $\phi$  of 80  $\mu\text{m}$ , the plated layer was formed by  
the nickel (II) sulfamate bath under the condition that the  
plated layer had a concave shape at the beginning of the  
20 electroplating. The concave profile of the plated layer  
remained even when the electroplating growth was  
continued until  $\Psi/2$  shown in Fig. 6 reached 200  $\mu\text{m}$ .  
Due to the concave profile of the plated layer, the thus-  
formed structure cannot be used as a microlens mold.

25 It was found through the above experiments that  
no difference in the minimum radius  $R_{\text{min}}$  of curvature  
appears even if the pitch or number of the openings

1 varies. Further, the result of the relationship between  
the radius of curvature and  $\Psi/2$  does not differ from the  
above even when a current flowing at the beginning of the  
electroplating under a voltage condition is measured and then  
5 the electroplating is continued under a constant current  
based on this measured amount of current.

Accordingly, where the plated layer has a flat portion  
when the plated layer is formed in the opening at  
the beginning of the electroplating growth, a microlens  
10 mold comprised of a substrate with the plated layer  
having a desired radius of curvature on its optical axis  
can be fabricated by meeting the relation (1).

In fabricating a microlens mold of this invention,  
an undesired profile error caused by over-etching  
15 proceeding until the washing step is conducted can be  
prevented. The deposition of the plated layer can be  
terminated when desired by terminating the current  
flowing between the anode and the cathode. Current  
flow is thus ended at the point where a desired  
20 profile is obtained. This contrasts with the method of  
forming a mold by etching, where etching proceeds  
until the washing step, thus causing a profile error.  
Accordingly, controllability of the fabrication is  
superior to the prior art method.

25 Further, the mold can be directly formed by  
electroplating. Therefore, no expensive equipment is  
needed, fabrication costs can be reduced, and the size

1 of the mold can be enlarged readily. Furthermore, the  
size of the plated layer can be controlled in situ,  
and the lens diameter and the like can be readily and  
precisely controlled by controlling electroplating time  
5 and temperature. When a plurality of openings are  
formed in the mask layer, a mold for a microlens array  
can be fabricated by the same method as above.

A process of fabricating a microlens using  
the above mold will now be described. Initially, an  
10 example of using the fabricated structure as a mold  
(not a mold master) for a microlens will be described  
with reference to Figs. 13A-13C. In Figs. 13A-13C, reference  
numeral 51 denotes a substrate, reference numeral 52  
denotes an electrode layer, reference numeral 53 denotes  
15 a mask layer, reference numeral 54 denotes an opening,  
reference numeral 55 denotes a plated layer, reference  
numeral 57 denotes a glass layer, reference numeral 58 denotes  
a resin having a large refractive index, and reference  
numeral 59 denotes an ultraviolet-ray curing resin.  
20 The microlens mold has a convex shape, and the plated  
layer 55 extends continuously as illustrated in Fig. 13A.  
The ultraviolet-ray curing resin 59 is laid over the  
mold fabricated by the above method. The glass layer 57  
is then placed on the resin 59, and the resin 59 is exposed  
25 to ultraviolet rays through the glass 57 to cure the  
resin 59. After that, the glass 57 and the resin 59 are  
separated from the mold. Thus, a concave microlens is



1 obtained. The concave microlens has the resin with an  
inverted profile of the plated layer 55 on the  
glass 57 as illustrated in Fig. 13B.

The resin 58 is then coated on the concave microlens,  
5 and the resin 58 is hardened and flattened. A complete  
microlens structure can be thus produced as illustrated  
in Fig. 13C.

In such a method of fabricating a microlens,  
alkaline glass is not necessarily required. Limitations  
10 to materials used for the microlens and for the support  
substrate are lowered, in contrast with the ion exchange  
method.

The above concave microlens may be fabricated by  
other methods, such as a method in which a conventional  
15 thermoplastic resin is used and a heated mold is stamped  
on this resin, a method in which a thermosetting resin  
is laid over a mold and then heated to be hardened, and  
a method in which an electron-beam curing resin is  
coated on a mold and the resin is hardened by  
20 electron beam irradiation.

An example of using the fabricated structure as  
a mold master (not a mold) for a microlens will be  
described. An electrode for electroplating a mold  
thereon is formed on a mold master for a microlens,  
25 and an electroplating material is electroplated on the  
electrode for electroplating a mold to form a  
microlens mold. The electroplating material differs

1 from a material used for the fabrication of the mold master.  
The mold is then separated from the mold master to obtain  
a concave mold for a microlens (see Figs. 11A-11E  
illustrating the example using the sacrificial layer).

5 An example of the fabrication process of a microlens  
using this concave mold will be described with reference  
to Figs. 12A-12C. A resin 40, such as an ultraviolet-ray  
curing resin, thermosetting resin or electron-beam  
curing resin, is coated on a concave mold 39, and  
10 after a support substrate 41 is laminated on resin 40,  
resin 40 is hardened by ultraviolet rays, heat or  
electron beam radiation. The resin 40 and the substrate 41  
are then separated from the mold 39 to obtain a  
microlens. A convex microlens can also be fabricated by  
15 stamping a heated mold on thermoplastic resin.

A second embodiment of a fabrication method of  
a mold for a microlens will be described with reference  
to Figs. 4, 8A-8D, 9 and 10. In the method of the second  
embodiment, a plated layer has a convex portion when  
20 electroplating is carried out in an opening during an initial  
electroplating growth step. In Figs. 8A-8D, reference  
numeral 11 denotes a substrate, reference numeral 12  
denotes an electrode layer, reference numeral 13 denotes  
a mask layer, reference numeral 14 denotes an opening,  
25 and reference numeral 15 denotes a plated layer.

The structure of substrate 11 illustrated in  
Fig. 8A will be described. The electrode layer 12

1 is formed on the substrate 11, and the mask layer 13  
is then formed thereon. Where the substrate 11 is  
composed of electrically-conductive material, there  
is no need to form electrode layer 12.

5        Opening 14 is then formed in the mask layer 13.  
Here, the opening 14 has a circular shape with a  
diameter  $\phi$ . The substrate 11 with the opening 14 acting  
as the base 21 is immersed in the electroplating bath 23  
containing metal ions of the electroplating apparatus  
10 illustrated in Fig. 4. The base 21 and the anode  
plate 22 are connected to the power source 24 to cause a  
current flow through the bath 23 and form the plated  
layer 15 in the opening 14. Thus, the convex plated  
layer 15 is initially formed in the opening 14 as  
15 illustrated in Fig. 8B. Herein, no flow of the  
electroplating liquid 23 occurs near opening 14 during  
the electroplating process. The reason and method  
therefor are described in the first embodiment. Also  
in this embodiment, a non-stirring electroplating method  
20 is used.

As the electroplating proceeds, the plated layer 15  
extends onto the mask layer 13 as illustrated in Fig. 8C,  
and the plated layer 15 with a curvature reflecting the  
convex profile at the beginning of the electroplating growth  
25 is formed. As the electroplating growth is further continued,  
the plated layer 15 develops a semispherical  
profile as illustrated in Fig. 8D. A semicylindrical

1 profile can be reached when the opening has a slit-like  
shape. Where the electroplating is carried out at a minute  
opening in the electroplating liquid containing metal  
ions, the metal ions move toward the plated layer,  
5 and hence, deposition of the electroplating proceeds  
with its growth direction being isotropic.

With the microlens mold to be fabricated according to  
the above-discussed method of the second embodiment, an  
experiment was carried out controlling parameters such as  
10 electroplating bath and electroplating conditions in order  
to obtain a mold having a minute semispherical profile.  
The condition for obtaining the initial convex plated  
layer 15 without the flat portion was determined when the  
plated layer was formed in the opening at the beginning  
15 of the electroplating growth (when  $\Psi = \phi$ ). It was found  
that the diameter  $\phi$  in this case should meet the  
following condition:

$$\phi \leq 10 \mu\text{m} \quad \dots (2).$$

When  $\Psi = \phi$ , the electroplating on a convex top  
20 portion of the plated layer 15 can be facilitated by  
making the initial plated layer 15 convex. As the plated  
layer 15 further grows, the plated layer 15 rapidly  
develops a semispherical profile. As a result, no  
difference appears between a radius of curvature on  
25 a side surface of the plated layer 15 and a radius of  
curvature near its optical axis, and hence, a side portion  
of a microlens to be fabricated by the above mold can be

1 used. Thus, a microlens with a large NA can be provided.

Where a semispherical profile needs to be obtained when  $\phi > 10 \mu\text{m}$ , the following is required as described in the first embodiment. The flat portion is formed at the beginning of the electroplating ( $\Psi = \phi$ ), and the plated layer is grown such that an approximately semispherical profile can be reached after the flat portion disappears. After that, the electroplating growth needs to be further continued. Therefore, in the method of the first embodiment, 10 the radius of curvature of the mold inevitably becomes relatively large. Accordingly, a microlens with a very minute radius of curvature (for example, less than  $30 \mu\text{m}$ ) is difficult to obtain.

A microlens with a very minute radius of curvature 15 can be provided when the above condition of the second embodiment is met. Further, since a semispherical profile can be obtained at the beginning of the electroplating, a microlens mold with a relatively large radius of curvature can also be achieved by further continuing the 20 electroplating growth.

Measurement of the radius of curvature and estimation of the semispherical profile will be described with reference to Fig. 9. A mask layer with a plurality of openings is formed on a substrate, electroplating is 25 performed by using the substrate as a base and the electroplating apparatus as illustrated in Fig. 4, and the the radius of curvature is obtained by measuring a

1 profile of the thus-formed plated layer right above the  
opening. More specifically, the radius of curvature of  
the microlens near its optical axis is determined by its  
surface profile, and a radius  $R$  of curvature in Fig. 9 is  
5 thus obtained. The surface profile is measured by the  
surface-shape measuring function which is one of the  
functions of the confocal scanning laser microscope. A  
measurement range is equal to a length of the opening  
diameter.

10 On the other hand, a virtual radius  $r$  of curvature  
indicated by a dotted line in Fig. 9 is calculated from  
a layer thickness  $H$  and a bottom diameter  $\Psi$  of the  
plated layer 15 (these  $H$  and  $\Psi$  are measured), on the  
assumption that the plated layer 15 has a semispherical  
15 profile. The radius  $r$  can be calculated as follows:

$$r = (\Psi \cdot \Psi / 4 + H \cdot H) / 2 \cdot H \quad \dots (3).$$

When the radius of curvature of a side of the plated  
layer 15 is equal to the radius of curvature near  
the optical axis, the radius  $R$  of curvature coincides  
20 with the virtual radius  $r$  of curvature and it can be  
hence said that the plated layer 15 has a semispherical  
profile. Conversely, it can be said that the plated  
layer 15 has a semispherical profile when the radius  $R$  of  
curvature coincides with the virtual radius  $r$  of curvature.  
25 A usable area of the lens can be thus expanded.

A experiment for finding conditions meeting those  
requirements was performed using Ni electroplating and Cu

1 electroplating. As an electroplating bath which relatively  
readily achieves the bright electroplating, the Watts  
bath was used in the Ni electroplating. The electroplating  
bath of copper sulfate electroplating was used in  
5 the Cu electroplating. The composition of the  
Watts bath was a water solution to which the brightener  
was added. This water solution consisted of nickel (II)  
sulfate hexahydrate, nickel (II) chloride hexahydrate and  
boric acid at a weight ratio per liter of 270 : 40 : 40,  
10 respectively. The temperature of the electroplating  
bath was set to 55 °C, and the Ni electroplating was  
performed under a constant voltage (an applied voltage  
is 1 V).

In the Cu electroplating, the composition of the  
15 bath was a water solution to which hydrochloric acid  
of 0.04 ml/l was added. This water solution consisted of  
copper (II) sulfate pentahydrate and sulfuric acid at a  
weight ratio per liter of 200 : 50. The temperature  
of the electroplating bath was set to 55 °C, and the Cu  
20 electroplating was performed under a constant voltage (an  
applied voltage is 0.3 V) as a bright condition of the  
plated layer. The above voltage is a voltage for achieving  
the convex plated layer 15 in the opening 14 in the  
initial electroplating step ( $\phi = \Psi$ ) and the bright electroplating.  
25 The same substrate 11 was used irrespective of  
the kind of the electroplating bath. This substrate will be  
described. The formation of the substrate 11 is the

1 same as the substrate 1 in the first embodiment, except  
for the size of the opening 14.

Herein, the opening 14 has a circular shape.

Measurements were carried out using opening diameters  
5 of 5  $\mu\text{m}$  and 10  $\mu\text{m}$ . As a comparison therewith, the  
same measurement was performed using an opening diameter  
of 20  $\mu\text{m}$ .

Fig. 10 shows results of measurements of the virtual  
radius of curvature and the radius of curvature  $R$  of  
10 the plated layer right above the opening 14 on the  
optical axis, in which substrates with plated layers  
having different radii were obtained in the Ni electroplating  
using the Watts bath and the Cu electroplating bath by  
varying electroplating times, respectively. In  
15 Fig. 10, a dotted line indicates  $R=r$ , black circles  
indicate the Cu electroplating bath ( $\phi=10\ \mu\text{m}$ ), blank  
circles indicate the Watts bath ( $\phi=10\ \mu\text{m}$ ), and blank  
squares indicate the Watts bath ( $\phi=5\ \mu\text{m}$ ). As is  
known from the case of the opening diameter  $\phi$  of 10  $\mu\text{m}$ ,  
20  $r=R$  in a range of  $r>20\ \mu\text{m}$  in this case, irrespective  
of the electroplating bath. In the case of the opening  
diameter of 5  $\mu\text{m}$ ,  $r=R$  at an early stage when  $r$  only  
reaches about 4  $\mu\text{m}$ .

As a comparative case, the same measurement was  
25 conducted using the opening diameter of 20  $\mu\text{m}$  in  
which the plated layer had the flat portion at the  
beginning of the electroplating growth ( $\Psi=\phi$ ). In the



1 plated layer of this microlens mold,  $r$  was not coincident  
with  $R$  even when  $r=70\ \mu\text{m}$ .

As a comparative case of the voltage condition, the  
plated layer was formed in the opening with a diameter  
5 of  $10\ \mu\text{m}$  under a voltage of  $3\ \text{V}$ , using the Watts bath.  
In this case, the plated layer was concave at the beginning  
of the electroplating growth ( $\Psi=\phi$ ), and the concave  
profile remained in the plated layer above the opening  
even when the bottom diameter of the plated layer reached  
10  $55\ \mu\text{m}$  during the following electroplating.

The results will be discussed concerning the same  
experiment performed using a opening diameter of  $10\ \mu\text{m}$   
and different mask material. Aromatic polyamideacid  
solution was spin-coated on the substrate and the mask  
15 layer 13 of polyimide was formed by heat treatment. The  
substrate 11 and the electrode layer 12 were the same  
as those in the first embodiment.

The opening 14 was formed in the following manner.  
Photoresist (product name: AZ1500 produced by Hoechst)  
20 was coated on the mask 13 by photolithography,  
and the resist was exposed and developed to form an  
opening therein. Thus, an etching mask was formed. The  
mask layer 13 at the opening in the photoresist was  
etched and removed by reactive ion etching using  
25 oxygen to expose the electrode layer 12. The opening 14  
was thus formed. The photoresist was thereafter removed.

Openings were arranged at intervals of  $200\ \mu\text{m}$ .

1 in a  $500 \times 500$  matrix pattern. The electrode layer 12 was  
used as the cathode, and a Watts bath containing  
nickel (II) sulfate, nickel (II) chloride, boric acid and  
brightener was used. The Ni electroplating was thus  
5 performed at the bath temperature of  $50^\circ\text{C}$  and the  
cathode current density of  $5\text{ A/dm}^2$ . Here, the bath  
(electroplating liquid) was not stirred. The Ni plated layer  
was initially deposited in the opening 14 and grew therein.  
The plated layer 15 expanded onto the mask layer 13; and  
10 the semispherical plated layer 15 was thus formed as  
illustrated in Fig. 8D. The plated layer was deposited  
until the bottom diameter of the plated layer reached  
 $50\text{ }\mu\text{m}$ .

Ten plated layers 15 were freely selected from the  
15 above structure of the microlens mold, and the radii  $R$  of  
curvature and the virtual radii  $r$  of curvature were  
measured.  $R$  and  $r$  were found incident with each other.  
Accordingly, a microlens mold with the semispherical  
plated layer having a radius of curvature of  $50\text{ }\mu\text{m}$   
20 can be provided in this case.

The electroplating experiment was then performed under  
a constant current using an opening diameter of  $5\text{ }\mu\text{m}$ .  
The substrate 11 and the electrode layer 12 were the  
same as above. That is, the substrate 11 was a silicon  
25 wafer which had layers of silicon dioxide with a thickness  
of  $1\text{ }\mu\text{m}$  formed on opposite surfaces of the wafer, and  
the electrode layer 12 was formed by continuously layering

1 Cr and Au on the substrate. The mask layer 13 was formed  
of a photoresist. Openings 14 were arranged at intervals  
of 25  $\mu\text{m}$  in a  $700 \times 700$  matrix pattern.

This wafer was used as a base, the electrode  
5 layer 12 was used as the cathode, and the Watts bath  
containing nickel (II) sulfate, nickel (II) chloride, boric  
acid and brightener was used. The Ni electroplating was  
thus performed at the bath temperature of 60  $^{\circ}\text{C}$  and two  
kinds of currents of 10 mA and 100 mA. Here, the bath  
10 was not stirred. The Ni plated layer was initially  
deposited in the opening 14 and grew therein. The  
plated layer 15 expanded onto the mask layer 13, and the  
semispherical plated layer 15 was thus formed as  
illustrated in Fig. 8D.

15 At each of those currents, the following substrates  
were formed. The plated layers 15 formed on the  
respective substrates had bottom diameters from 10  $\mu\text{m}$   
to 35  $\mu\text{m}$  at intervals of 5  $\mu\text{m}$ . In each microlens  
mold, ten plated layers 15 were freely selected from the  
20  $700 \times 700$  plated layers, and the radius of curvature R and  
the virtual radius r of curvature were measured for  
each selected plated layer. R and r were found incident  
with each other. A microlens mold with the semispherical  
plated layer having a minute radius of curvature can  
25 thus be provided by electroplating under a constant  
current, similar to that under a constant voltage.

From the above results, it was found that there is

1 no difference between the radius of the side of the  
plated layer 15 and the radius of curvature near the  
optical axis. Therefore, the side surface of a microlens  
fabricated by the above mold can be used and a lens  
5 with a large NA can be provided where the condition of  
the convex plated layer 15 without the flat portion is met,  
when the bottom diameter  $\Psi$  of the plated layer 15  
coincides with the opening diameter  $\phi$  and no plated  
layer is grown on the mask layer 13. Herein, the opening  
10 diameter meets the relation (3).

Also in the second embodiment, the same technical  
advantages as those of the first embodiment can be  
obtained. Further, a preferable microlens can be fabricated  
using the above mold.

15 The following is an example in which a microlens  
mold is fabricated based on the principle of the second  
embodiment using the Cr electroplating bath. A fused quartz  
glass of six square inches is used as the substrate 11.  
To form the electrode layer 12, Cr and Au are continuously  
20 layered at thicknesses of 10 nm and 200 nm on the  
above substrate, respectively, using the electron beam  
vacuum-evaporation method which is one of the thin-film  
forming methods.

Coating, exposure and development of a photoresist  
25 are performed using photolithography to form the  
opening 14 in the resist. The photoresist is used as the  
mask layer 13.

1        Herein, the opening 14 has a circular shape. and the  
diameter  $\phi$  and pitch of the opening 14 are respectively  
5  $\mu\text{m}$  and 35  $\mu\text{m}$ . Each block has the above arrangement  
of the openings 14 in a  $100 \times 100$  matrix pattern.  $8 \times 8$   
5 blocks are arranged at inter-block intervals of 20 mm  
on the substrate 11.

The Cr electroplating is performed using the electrode  
layer 12 as the cathode and using the Cr electroplating bath  
containing chromic acid and sulfuric acid. The Cr plated layer  
10 is initially deposited on the electrode layer 12 in  
the opening 14, and the plated layer 15 has a convex  
profile when the plated layer is formed in the opening 14.  
After that, the plated layer 15 expands onto the mask  
layer 13 as the electroplating further continues. The  
15 plated layer 15 having a semispherical profile is thus  
formed. The electroplating is continued until the radius  
of the semispherical profile reaches 70  $\mu\text{m}$ , and the  
continuous plated layer 15 is formed.

A microlens array is formed using the above mold  
20 with the semispherical Cr plated layer 15. As  
illustrated in Fig. 13A, the ultraviolet-ray curing  
resin 59 is dropped on the mold 51-55. The glass  
substrate 57 is then placed on the resin 59, and the  
resin 59 exposed to ultraviolet radiation through the  
25 glass 57 to cure the resin 59. After that, the glass 57  
and the resin 59 are separated from the mold. Thus, the  
concave microlens array 59 is obtained. The concave

1 microlens has an inverted profile of the mold on the  
glass 57 as illustrated in Fig. 13B.

An ultraviolet-ray curing resin 58 is coated  
on the concave microlens. The resin 58 has a larger  
5 refractive index than that of the resin 59. A glass  
substrate is put on the resin 58 to flatten the surface  
of the resin 58. The resin 58 is exposed to ultraviolet  
rays to be hardened. The glass substrate is separated  
from the hardened ultraviolet-ray curing resin 58. A  
10 complete microlens array can be thus produced as  
illustrated in Fig. 13C.

Using the same microlens mold, a thousand pieces  
of the above microlens arrays were repeatedly produced  
by the same method. After that, the surface of the  
15 microlens mold of the second embodiment was observed.  
No corrosion, scratches and the like could be seen.

In a third embodiment, Pt is used as an electrode  
layer 32. The third embodiment will be described with  
reference to Figs. 11A-11E. A substrate of this  
20 embodiment is produced similarly to the first embodiment.

A silicon wafer with a diameter of six inches is  
thermally oxidized using an oxidizing gas, and layers of  
silicon dioxide with a thickness of 1  $\mu\text{m}$  are formed on  
opposite surfaces of the wafer. This wafer is used as  
25 a substrate 31 illustrated in Figs. 11A-11E. Ti and  
Pt are sequentially deposited with thicknesses of 10 nm  
and 200 nm on the above wafer, respectively, using

1 a vacuum sputtering method which is one of thin-film  
forming methods. The electrode layer 32 is thus formed.  
Aromatic polyamideacid solution is then spin-coated,  
and this coating is thermally treated to form a mask  
5 layer 33 of polyimide.

Further, coating, exposure and development of  
photoresist are performed using conventional  
photolithography to form an opening in the resist. The  
mask layer 33 at the resist opening is etched by the  
10 reactive ion etching using oxygen. Thus, the electrode  
layer 32 is exposed and the opening 34 is formed. The  
photoresist is removed thereafter.

Herein, the opening 34 has a circular shape with  
a diameter of 10  $\mu\text{m}$ . Openings 34 are arranged at  
15 intervals of 200  $\mu\text{m}$  in a  $500 \times 500$  matrix pattern. The  
electrode layer 32 is used as a cathode, and a Ni  
electroplating bath containing nickel (II) sulfate,  
nickel (II) chloride, boric acid and brightener is used.  
Ni electroplating is thus performed at the bath  
20 temperature of 50  $^{\circ}\text{C}$  and the cathode current density  
of 5  $\text{A}/\text{dm}^2$ . A Ni plated layer 35 is initially deposited  
in the opening 34 and grows therein. The plated layer  
expands onto the mask layer 33, and the semispherical  
plated layer 35 is thus formed as illustrated in Fig.  
25 The plated layer 35 is deposited until its radius  
reaches 50  $\mu\text{m}$ . This can be confirmed by using a  
microscope, for example.

1 PSG (phospho-silicate glass) with a thickness of  
1  $\mu\text{m}$  is then deposited at 350 °C by a atmospheric-  
pressure CVD (chemical vapor deposition) method to form a  
sacrificial layer 37 as illustrated in Fig. 11A. Ti  
5 and Au are continuously layered with thicknesses  
of 10 nm and 200 nm on the above wafer, respectively,  
using an electron-beam evaporation method. An electrode  
layer 38 for a mold is thus formed as illustrated in  
Fig. 11B.

10 The electrode layer 38 is then used as a cathode, and  
the above Ni electroplating bath is used. Ni electroplating  
is thus performed at the bath temperature of 50 °C and the  
cathode current density of 5 A/dm<sup>2</sup>. A mold 39 is thus  
formed as illustrated in Fig. 11C.

15 The wafer of Fig. 11C is then immersed in a mixture  
solution of hydrofluoric acid and ammonium fluoride  
to etch and remove the sacrificial layer 37 of PSG. The  
substrate 31 and the mold 39 can be separated as  
illustrated in Fig. 11D. The Ti of the electrode  
20 layer 38 can be removed simultaneously. After that, the  
electrode layer 38 is etched by a mixture solution of  
iodine and potassium iodide. The mold 39 for a microlens  
can be thus produced as illustrated in Fig. 11E.

The separated substrate has a semispherical  
25 structure as illustrated in Fig. 11A, except for the  
sacrificial layer 37. Therefore, a mold for a microlens  
can be repeatedly produced by performing the steps of



1 Figs. 11A-11E using this separated substrate.

In a fabrication method of a microlens mold according to this embodiment, the mold can be fabricated by electroplating. Accordingly, a plurality of molds  
5 with the same profile can be produced. Thus, plural molds can be fabricated in this embodiment by using the mold master and the sacrificial-layer forming process, in contrast with the prior art mold forming method in which a single original mold is used. Hence, fabrication costs  
10 can be further reduced in this embodiment.

A fabrication process of a microlens using this concave mold will be described with reference to Figs. 12A-12C. A resin 40 of ultraviolet-ray curing photopolymer is deposited on the concave mold 39, and  
15 after a support substrate 41 of glass is put on the resin 40, the resin 40 is hardened by exposing the resin 40 to ultraviolet rays. The resin 40 can be separated from the microlens mold 39 by lifting the glass substrate 41. Thus, a microlens array can be formed.  
20 Here, a thousand photopolymer microlenses could be formed by the same microlens mold, using the same method.

In a fourth embodiment, an electrode layer 32 is formed of the same material as that of a plated layer 35. The fourth embodiment will also be described with  
25 reference to Figs. 11A-11E.

A substrate of this embodiment is also produced similarly to the first embodiment. A silicon wafer

1 with a diameter of six inches is thermally oxidized using  
an oxidizing gas, and layers of silicon dioxide with a  
thickness of  $1\ \mu\text{m}$  are formed on opposite surfaces of the  
wafer. This wafer is used as a substrate 31 illustrated  
5 in Figs. 11A-11E. Ti and Ni are continuously layered  
with thicknesses of 10 nm and 200 nm on the above  
wafer, respectively, using the vacuum sputtering  
method which is one of thin-film forming methods. The  
electrode layer 32 is thus formed. Aromatic polyamide  
10 acid solution is then spin-coated and this coating  
is thermally treated to form a mask layer 33 of  
polyimide.

Further, coating, exposure and development of  
photoresist are performed using photolithography to  
15 form an opening in the resist. The mask layer 33 at the  
resist opening is etched by the reactive ion etching  
using oxygen. Thus, the electrode layer 32 is exposed,  
and the opening 34 is formed. The photoresist is removed  
thereafter.

20 Herein, the opening 34 also has a circular shape  
with a diameter of  $10\ \mu\text{m}$ . Openings 34 are arranged  
at intervals of  $200\ \mu\text{m}$  in a  $500 \times 500$  matrix pattern.  
The electrode layer 32 is used as a cathode, and a Ni  
electroplating bath containing nickel (II) sulfate,  
25 nickel (II) chloride, boric acid and brightener is used.  
Ni electroplating is thus performed at the bath  
temperature of  $50\ ^\circ\text{C}$  and the cathode current density

1 of 5 A/dm<sup>2</sup>. The Ni plated layer 35 is initially deposited  
in the opening 34 and grows therein. The plated layer 35  
expands onto the mask layer 33, and the semispherical  
plated layer 35 is thus formed as illustrated in Fig. 11A.  
5 The plated layer 35 is deposited until its radius  
reaches 50  $\mu$ m. This can be confirmed by using a  
microscope.

Since the material of the electrode layer 32 is the  
same as that of the plated layer 35, there is no mismatch  
10 of crystalline lattices between those layers 32 and 35  
which is likely to occur between different materials.  
Therefore, the plated layer 35 can be smoothly formed on  
the electrode layer 32, and the semispherical structure  
can be firmly connected to the electrode layer 32. Thus,  
15 the semispherical structure would not separate during the  
cleansing process and the like, so the wafer can be  
readily handled.

PSG with a thickness of 1  $\mu$ m is then deposited  
at 350 °C by the atmospheric-pressure CVD method to form a  
20 sacrificial layer 37 as illustrated in Fig. 11A. Ti and  
Au are continuously layered with thicknesses of 10 nm  
and 200 nm on the above wafer, respectively, using the  
electron-beam evaporation method. An electrode layer 38  
for a mold is thus formed as illustrated in Fig. 11B.

25 The electrode layer 38 is then used as a cathode,  
and the above Ni electroplating bath is used. Ni  
electroplating is thus performed at the bath temperature

1 of 50 °C and the cathode current density of 5 A/dm<sup>2</sup>.

A mold 39 is thus formed as illustrated in Fig. 11C.

The wafer of Fig. 11C is then immersed in a mixture solution of hydrofluoric acid and ammonium fluoride to  
5 etch and remove the sacrificial layer 37 of PSG. The substrate 31 and the mold 39 can be separated as illustrated in Fig. 11D. The Ti of the electrode layer 38 can be removed simultaneously. After that, the electrode layer 38 is etched by a mixture solution of iodine and  
10 potassium iodide. The mold 39 for a microlens can be thus produced as illustrated in Fig. 11E.

The separated substrate has a semispherical structure as illustrated in Fig. 11A, except for the sacrificial layer 37. Therefore, a mold for a microlens  
15 can be repeatedly produced by performing the steps of Figs. 11A-11E using this separated substrate.

Regarding other points, the fourth embodiment is substantially the same as the third embodiment.

In a fifth embodiment, an electrode layer 32 is  
20 formed of material which can be easily diffused into a plated layer 35. The fifth embodiment will also be described with reference to Figs. 11A-11E.

A substrate of this embodiment is also produced similarly to the first embodiment. A silicon wafer  
25 with a diameter of six inches is thermally oxidized using an oxidizing gas, and layers of silicon dioxide with a thickness of 1  $\mu$ m are formed on opposite surfaces of the

1 wafer. This wafer is used as a substrate 31 illustrated  
in Figs. 11A-11E. Ti and Au are continuously layered with  
thicknesses of 10 nm and 200 nm on the above wafer,  
respectively, using the vacuum sputtering method. The  
5 electrode layer 32 is thus formed. Aromatic polyamide  
acid solution is then spin-coated and this coating  
is thermally treated to form a mask layer 33 of  
polyimide.

Further, coating, exposure and development of  
10 photoresist are performed using the photolithography to  
form an opening in the resist. The mask layer 33 at the  
resist opening is etched by reactive ion etching  
using oxygen. Thus, the electrode layer 32 is exposed  
and the opening 34 is formed. The photoresist is removed  
15 thereafter.

Herein, the opening 34 also has a circular shape  
with a diameter of 10  $\mu\text{m}$ . Openings 34 are arranged  
at intervals of 200  $\mu\text{m}$  in a 500 $\times$ 500 matrix pattern.  
The electrode layer 32 is used as a cathode, and a Ni  
20 electroplating bath containing nickel (II) sulfate,  
nickel (II) chloride, boric acid and brightener is used.  
Ni electroplating is thus performed at the bath  
temperature of 50  $^{\circ}\text{C}$  and the cathode current density  
of 5 A/dm<sup>2</sup>. The Ni plated layer 35 is initially deposited  
25 in the opening 34 and grows therein. The plated layer 35  
expands onto the mask layer 33, and the semispherical  
plated layer 35 is thus formed as illustrated in

1 Fig. 11A. The plated layer 35 is deposited until its  
radius reaches 50  $\mu\text{m}$ . This can be confirmed by using a  
microscope.

Herein, the electrode layer 32 is diffused into the  
5 plated layer 35. This was verified by the fact that a  
diffusion layer of an alloy of nickel and gold could  
be found around the electrode layer 32 at the opening 34  
when the thus-formed semispherical structure was  
dissolved in sulfuric acid solution. Thus, Au of the  
10 electrode layer 32 is diffused into the plated layer 35  
of nickel, and the semispherical structure can be firmly  
connected to the electrode layer 32. Hence, the  
semispherical structure would not separate during the  
cleansing process and the like, so the wafer can be  
15 readily handled.

PSG with a thickness of 1  $\mu\text{m}$  is then deposited  
at 350  $^{\circ}\text{C}$  by the atmospheric-pressure CVD method to form a  
sacrificial layer 37 as illustrated in Fig. 11A. Ti  
and Au are continuously layered with thicknesses of  
20 10 nm and 200 nm on the above wafer, respectively, using  
the electron-beam evaporation method. An electrode  
layer 38 for a mold is thus formed as illustrated in  
Fig. 11B.

The electrode layer 38 is then used as a cathode,  
25 and the above Ni electroplating bath is used. Ni  
electroplating is thus performed at the bath temperature  
of 50  $^{\circ}\text{C}$  and the cathode current density of 5  $\text{A}/\text{dm}^2$ . A

1 mold 39 is thus formed as illustrated in Fig. 11C.

The wafer of Fig. 11C is then immersed in a mixture solution of hydrofluoric acid and ammonium fluoride to etch and remove the sacrificial layer 37 of PSG. The substrate 31 and the mold 39 can be separated as illustrated in Fig. 11D. The Ti of the electrode layer 38 can be removed simultaneously. After that, the electrode layer 38 is etched by a mixture solution of iodine and potassium iodide. The mold 39 for a 10 microlens can be thus produced as illustrated in Fig. 11E.

The separated substrate has a semispherical structure as illustrated in Fig. 11A, except for the sacrificial layer 37. Therefore, a mold for a microlens 15 can be repeatedly produced by performing the steps of Figs. 11A-11E using this separated substrate.

Regarding other points, the fifth embodiment is substantially the same as the third embodiment.

In a sixth embodiment, a mold is fabricated using 20 another method. The sixth embodiment will also be described with reference to Figs. 11A-11E.

A semispherical structure of a plated layer 35 is formed on a substrate 31 with an electrode layer 32, a mask layer 33 and an opening 34 by the same method as 25 that of the third embodiment. PSG with a thickness of 1  $\mu$ m is then deposited at 350 °C by the atmospheric-pressure CVD method to form a sacrificial layer 37 as illustrated

1 in Fig. 11A. Ti and Au are continuously layered with  
thicknesses of 10 nm and 200 nm on the above wafer,  
respectively, using the electron-beam evaporation  
method. An electrode layer 38 for a mold is thus formed  
5 as illustrated in Fig. 11B to fabricate a mold master.

The electrode layer 38 is then used as a cathode, and  
a Ni electroplating bath containing nickel (II) sulfamate,  
nickel bromide, boric acid and brightener is used. Ni  
electroplating is thus performed at the bath temperature  
10 of 50 °C and the cathode current density of 5 A/dm<sup>2</sup>. A  
mold 39 is thus formed as illustrated in Fig. 11C.

The wafer of Fig. 11C is then immersed in a mixture  
solution of hydrofluoric acid and ammonium fluoride  
to etch and remove the sacrificial layer 37 of PSG. The  
15 substrate 31 and the mold 39 can be separated as  
illustrated in Fig. 11D. The Ti of the electrode layer 38  
can be removed simultaneously. After that, the electrode  
layer 38 is etched by a mixture solution of iodine and  
potassium iodide. The mold 39 for a microlens can be  
20 thus produced as illustrated in Fig. 11E.

Since the nickel (II) sulfamate bath is used as the  
electroplating bath, warping of the mold due to electroplating  
stress can be reduced or eliminated.

Regarding other points, the sixth embodiment is  
25 substantially the same as the third embodiment.

In the foregoing this invention is described using  
a microlens mold or a microlens array mold. The principle



1 of this invention, however, can be more broadly applied  
to a microstructure having the above-discussed structural  
features and a mold for a microstructure.

Further, the opening has a circular shape in the  
5 above embodiments, but the opening can have other shapes,  
such as a slit-like shape or an elongated rectangular  
shape. When the opening has the slit-like shape, a  
semicylindrical plated layer can be formed and a mold  
for a lenticular lens or a lenticular lens array can be  
10 fabricated, for example. Fig. 14 illustrates a lenticular  
lens mold 62 fabricated on a substrate 61 according to  
the above method.

As described in the foregoing, when the microlens  
mold of this invention meets the relation (1) regarding  
15 the opening diameter  $\phi$ , the mold can have a desired  
radius of curvature on the optical axis.

Further, when the microlens mold of this invention  
meets the condition that the opening diameter is  
below  $10\ \mu\text{m}$ , the mold can have a desired structure in  
20 which the radius of curvature of the side of the plated  
layer is about equal to the radius of curvature near the  
optical axis. The microlens fabricated using this  
mold can be a lens with a large NA.

Further, in the fabrication method of the microlens  
25 mold of this invention, where the plated layer formed  
in the opening at the beginning of the electroplating  
growth has the flat portion, the mold having the

1 plated layer with a desired radius of curvature on the  
optical axis can be fabricated when the relation (1) is  
met.

Furthermore, in the fabrication method of the  
5 microlens mold of this invention, where the plated  
layer formed in the opening at the beginning of the  
electroplating growth is the convex layer without the  
flat portion, the radius of curvature of the side of  
the plated layer is about equal to the radius of curvature  
10 near the optical axis and the microlens fabricated  
using this mold can have a usable side. Thus, the lens  
with a large NA can be provided.

Meanwhile, conditions for forming the above plated  
layer are independent of the kind of the electroplating  
15 bath used.

Thus, according to the present invention, a minute  
microlens with a radius of curvature below several  
hundreds of microns (especially, below about  $300\ \mu\text{m}$ ), or with  
a top portion's radius of curvature below  $200\ \mu\text{m}$ , can  
20 be fabricated with good, precise profile.

While the present invention has been described  
with respect to what are presently considered to be the  
preferred embodiments, it is to be understood that the  
invention is not limited to the disclosed embodiments.  
25 The present invention is intended to cover various  
modifications and equivalent arrangements included  
within the spirit and scope of the appended claims.